The Influence of Buoyancy and Stratification on Circulation, Mixing, and Bottom Stress in Complex Channel/Tidal Flat Systems: A Process Oriented and Realistic Numerical Modeling Study

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LONG-TERM GOALS

This effort represents a step towards understanding the dynamics that drive the circulation in estuarine, tidal flat and inner-continental-shelf coastal environments with complex bathymetry, shallow water depths, and strong forcing by tides, river flow, wind and waves, and determining how these circulation patterns and their variability control the pathways of transport of waterborne materials – including sediments, nutrients and anthropogenic materials – through these regions and into the adjacent coastal ocean. Specifically, we aim to develop realistic, high-resolution numerical simulations of such environments that resolve the bathymetric variability and are capable of simulating small-scale coherent structures (for example, flow separation, eddies, and secondary flows) that regulate dispersion and transport of materials within these systems. Essential to this effort is validating such models through skill assessment via statistical comparisons between model output and field measurements over a broad range of forcing conditions.

OBJECTIVES

The principle objective of this effort is to develop a high-resolution numerical simulation of the Skagit River delta (Fig. 1a), in Puget Sound, Washington – a complex region with broad tidal flats and complex channel networks and one of the focal systems of the ONR Coastal Geosciences Tidal Flats Departmental Research Initiative (DRI). Our specific objectives in this project are to use this numerical model to:

- Determine the temporal (tidal and sub-tidal) and spatial variations of buoyancy and stratification and their dependence on freshwater discharge, tidal amplitude, and wind forcing.
- Quantify the roles of tides, buoyancy forcing, and winds in driving the three-dimensional circulation within channels and over tidal flats under different forcing regimes.
- Understand how buoyancy, buoyancy fronts, and barotropic fronts regulate vertical mixing and bottom shear stresses within channels and over tidal flats and how these control sediment suspension, transport and deposition patterns.

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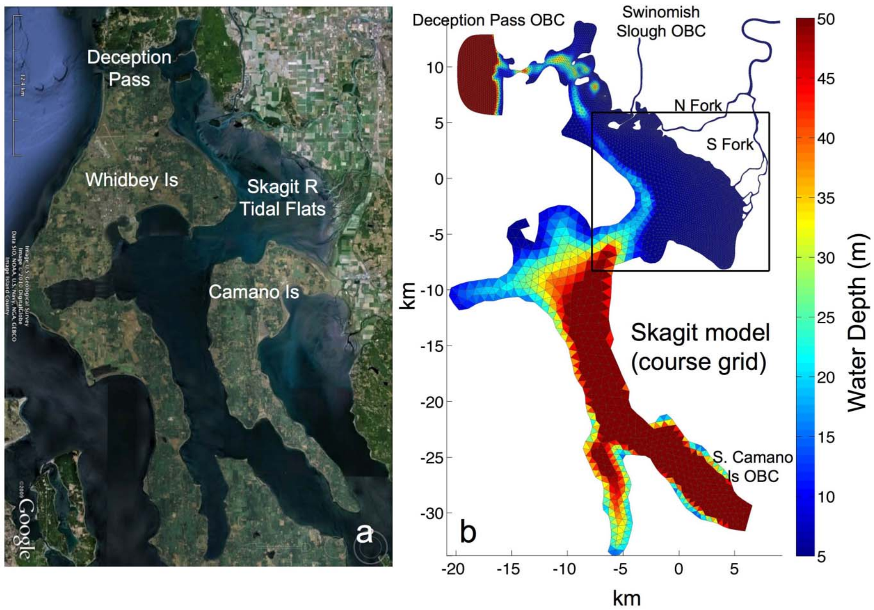

Figure 1. a) Aerial photograph of the Skagit River delta and adjacent waters in Puget Sound, WA (adapted from Google Earth). b) Medium-resolution FVCOM grid. Triangles indicate computational grid cells. Cell color indicates water depth at cell centroids. The black box shows the Skagit tidal flat region (Fig. 2).

Several collaborative modeling projects were supported under the Tidal Flats DRI, including those led by David Ralston (Woods Hole Oceanographic Institution) and Geoff Cowles (University of Massachusetts, Dartmouth). This project broadens the Tidal Flat DRI objectives by quantifying the variability in hydrodynamics and bottom stresses caused by the range of forcing conditions occurring over the Skagit River region over seasonal and inter-annual time scales.

APPROACH

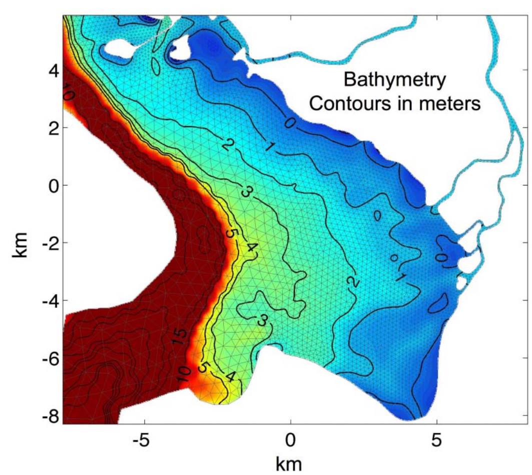

Figure 2. Skagit River tidal flat region of the medium-resolution FVCOM domain. Triangles indicate computational cells. Minimum cell size over the flats is about 100 m. Color shading and contours indicate water depth

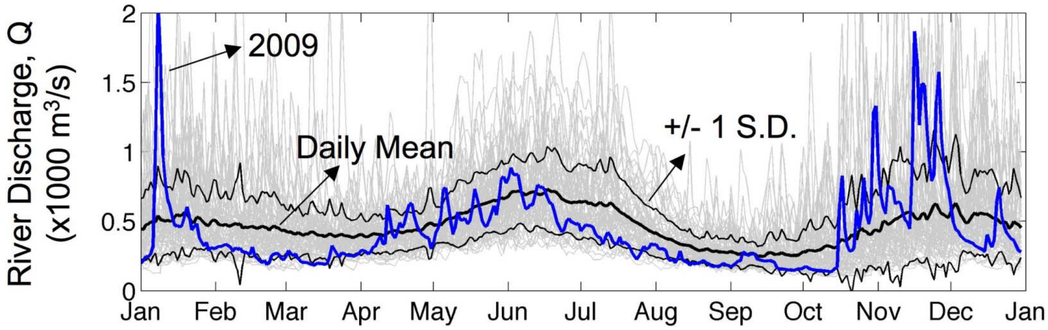

Figure 3. Annual variations in Skagit River discharge based on data from USGS stream gage number 12200500. Gray lines show daily discharge from 1940-2010. The thick line is average daily discharge based on 70 year stream gage record. Thin lines indicate +/- one standard deviation about the average. The blue line shows daily discharge in 2009, the main year of Tidal Flat DRI field studies.

Our modeling effort utilizes the Finite Volume Coastal Ocean Model (FVCOM; Chen et al., 2003, 2006), an unstructured-grid, finite-volume numerical model that allows for accurate representation of complicated domains. Flexible, spatially-heterogeneous grids can be constructed so that high spatial resolution is applied only to regions where it is necessary. This flexibility is essential for domains with a wide range of bathymetric scales such as tidal flats and channel networks. A mass-conserving, wetting/drying scheme has been implemented in FVCOM, allowing for flooding/drying over tidal flats. State-of-the-art, two-equation turbulence closure schemes have been implemented in FVCOM using the General Ocean Turbulence Model (GOTM) libraries (Chen et al., 2008). Surface forcing capabilities include wind stress, heat flux, and precipitation flux. In addition, the NOPP sponsored Community Sediment Transport Model (CSTM; http://woodshole.er.usgs.gov/project-pages/sediment-transport; Warner et al., 2008) has been implemented in FVCOM.

Two model grids have been developed. The first is a high spatial-resolution grid of the Skagit River, tidal flats and adjacent waters in Puget Sound, Washington, with minimum horizontal computational cell size of about 20 m over the tidal flats. The second medium-resolution grid (Figs. 1b and 2) spans the same domain as the high-resolution grid, but has a minimum grid cell size of about 100 m over the tidal flats (Fig. 2). Extensive validation of the model, based on comparisons to data collected as part of the Tidal Flat DRI, has been conducted by David Ralston. In this study, we primarily use the medium-resolution grid in order to complete the long simulations (annual and inter-annual) in a reasonable time frame. The model is forced by tidal sea level fluctuations at three open boundaries (Deception Pass, Swinomish Slough, and South Camano Island). Freshwater discharge enters the domain through the up-river boundary of the Skagit River. Wind stress forcing will be included in future simulations.

WORK COMPLETED

The focus in this second year of the project has been on studying the impact of seasonal variations in river discharge and inter-annual variations in winter storm discharge on tidal flat hydrodynamics and bottom stresses. Skagit River discharge typically peaks in late fall/early winter due to winter storms

and during the late spring/early summer freshet associated with snow melt (Fig. 3). Minimum river discharge typically occurs in late summer/early fall. Large variability in discharge amplitude also **occurs at synoptic (storm event) and inter-annual time scales (Fig. 4a). Simulations were run**

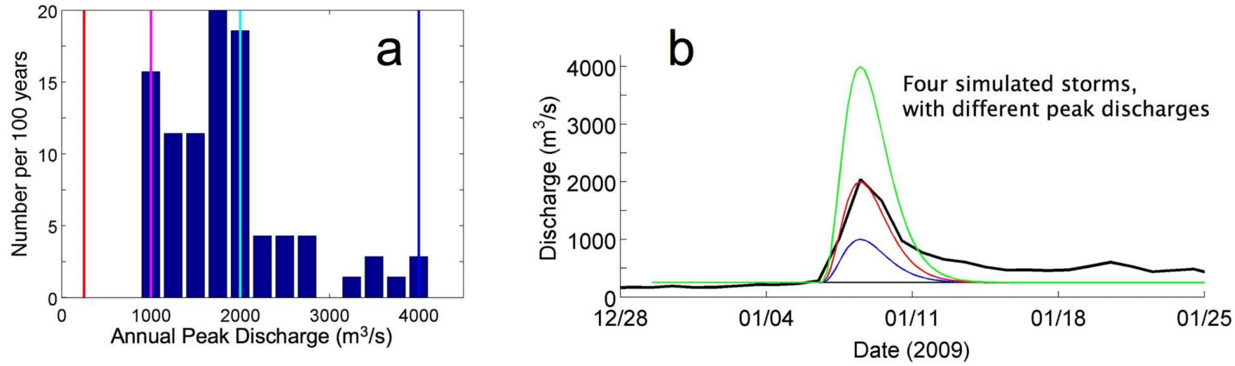

Figure 4. a) Frequency of annual peak discharge, scaled to give number of occurrences in 100 years of annual peak discharge within a specified range. b) Idealized storm hydrograph with peak discharge amplitude ranging from 0 to 400 m^3/s used in simulations to study tidal flat response to a storm event.

under a range of realistic discharge and tide conditions observed in 2009, the main field year of the Tidal Flat DRI – for example, January storm (mean discharge = 690 m^3/s, std. dev. = 440 m^3/s), spring/summer freshet (mean discharge = 720 m^3/s, std. dev. = 100 m^3/s), fall low discharge (mean discharge = 150 m^3/s, std. dev. = 11 m^3/s), and fall storms (mean discharge = 790 m^3/s, std. dev. = 400 m^3/s). In addition, simulations were run for idealized storm events with different peak discharge (Fig. 4b). Results from these simulations are summarized in the next section.

RESULTS

For the simulations forced with realistic discharge and tides observed in 2009, we focus here on two periods – low discharge during the early fall and strong and variable discharge during the late fall storm period (Fig. 3). Stratification over the flats is strongly dependent on river discharge (Fig. 5). During low discharge, mean stratification is weak over most of the tidal flat, with strong stratification confined to locations where the north and south forks of the Skagit enter the tidal flats. During strong discharge in late fall of 2009, strong stratification extends over most of the tidal flat region.

Bottom stress over the tidal flats is also strongly dependent on strength of river discharge. For example, here we decompose the bottom stress variability into three spatial time scales: overall mean, variability at sub-tidal (low-frequency) time scales, and variability at tidal time scales (Fig. 6). During

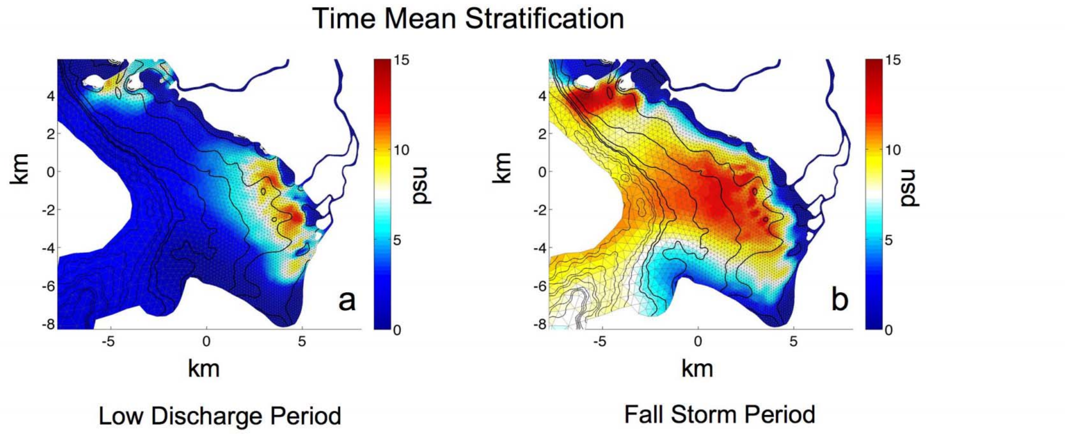

Figure 5. Mean stratification (top-to-bottom salinity difference) over Skagit tidal flats during a) low discharge in early fall and b) high and variable discharge in late fall of 2009.

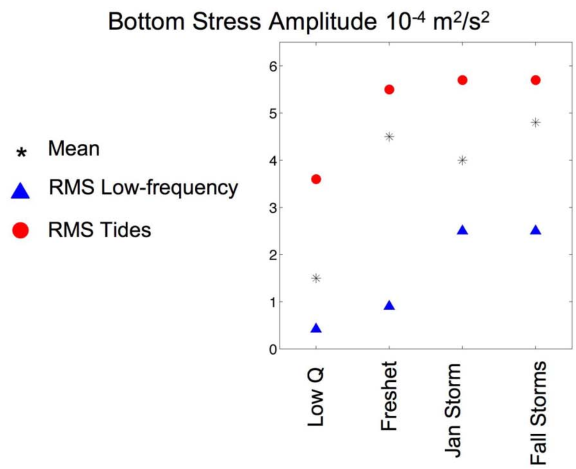

Figure 6. Influence of river discharge amplitude and variability on bottom stress over the Skagit tidal flats. Bottom stress is averaged over the tidal flat region and decomposed into three time scales of variability: time mean, sub-tidal (low-frequency), and tidal. Values for four periods in 2009 with different river discharge characteristics are shown.

low discharge in early fall of 2009, mean and sub-tidal bottom stress variability are weak. During periods of high discharge, mean and sub-tidal bottom stress increase, with RMS sub-tidal discharge approaching the size of tidal-scale variability, particularly during the late fall storm period.

For a particular idealized storm event (Fig. 4b), bottom stress is highly dependent on storm discharge amplitude (Fig. 7). For example, vertically-averaged current amplitude near where the river channels enter the flats is about three times greater when peak storm amplitude is 4000 m^3/s compared to the case without a storm event (Fig. 7), resulting in an approximately nine-fold increase in bottom stress at these locations for extreme storms.

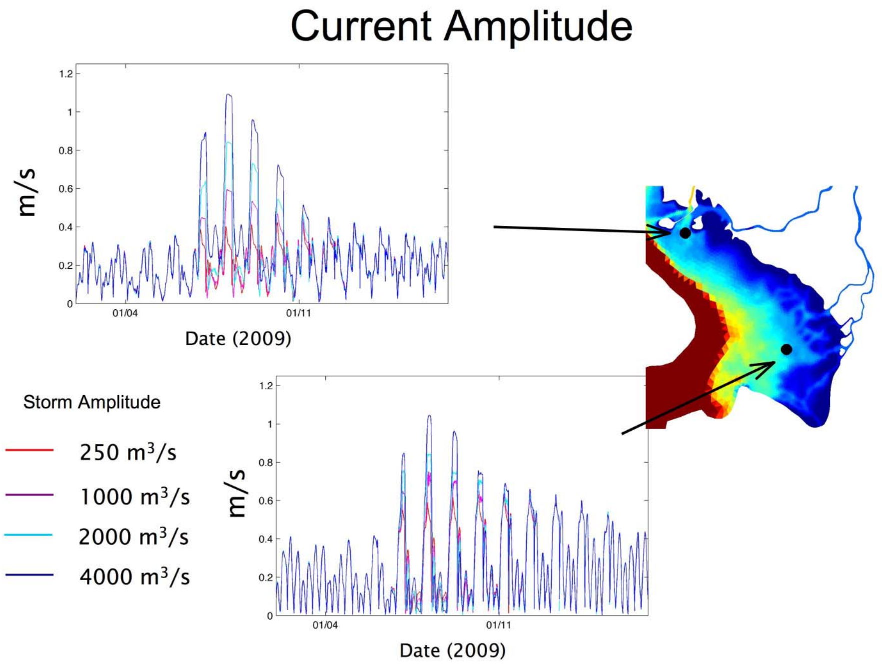

Figure 7. Time series of vertically-averaged current amplitude during an idealized storm event with different peak amplitudes (Fig. 4b). Time series are plotted for two locations on the Skagit tidal flats, near where the north and south forks of the river enter the flats.

A manuscript on this study is currently in preparation and will be submitted to the Tidal Flats Special Issue of Continental Shelf Research in the winter of 2010.

IMPACT/APPLICATIONS

This modeling effort is testing the capabilities of state-of-the-art hydrodynamic models at simulating the detailed circulation of strongly-forced, bathymetrically complex regions and expanding the scope of the Tidal Flat DRI to include a study of the storm event, seasonal and inter-annual variability in the hydrodynamics of the region. Such models can be applied to a wide range of applications including the study of: tidal flat morphodynamics; the dynamics of coherent structures observed via remote sensing and their relationship to bottom bathymetry; the influence of sea-level rise on tidal flat dynamics; and the prediction of currents over tidal flats.

RELATED PROJECTS

This effort is being conducted in collaboration with scientists in the Coastal Geosciences Tidal Flats DRI (http://tidalflats.org/index.html), especially David Ralston and Geoff Cowles.

REFERENCES

Chen, R.C., J. Qi, C. Li, R. Beardsley, H. Lin, R. Walker, and K. Gates (2008), Complexity of the Flooding/Drying Process in an Estuarine Tidal-Creek Salt-Marsh System: An Application of FVCOM, *J. of Geophysical Res.*, **113**, C7.

Chen, C, R. C. Beardsley and G. Cowles, (2006). An unstructured grid, finite-volume coastal ocean model (FVCOM) system. Special Issue entitled "Advance in Computational Oceanography", *Oceanography*, **19**(1), 78-89.

Chen, C., H. Liu, and R. Beardsley, (2003). An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries. *Journal of Atmospheric and Ocean Technology*, **20** (1), 159–186.

Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., and Arango, H. G. (2008) Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. *Computers & Geosciences*, **34**(10), 1284-1306.